RFI MITIGATION AND DETECTION FOR THE SMAP RADAR

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ABSTRACT

The planned Soil Moisture Active Passive (SMAP) mission[1] will use both active radar and passive radiometer instruments at L-Band to measure and monitor both soil moisture and freeze/thaw state globally. The frequency band allocated for the SMAP radar is shared with the Global Navigation Satellite Systems and ground-based radiolocation services. Signals from those users present significant sources of anthropogenic radio frequency interference (RFI) which contaminate the radar measurements. To mitigate RFI, the radar is designed with tunable operating frequency, which allows the center frequency to be tuned to avoid RFI. The filtering scheme in the receiver is configured to get a high level of RFI suppression. To meet the high accuracy measurement requirements, RFI detection and correction will be required during ground data processing. Some candidate algorithms have been evaluated, and they have been tested against simulated SMAP data derived from the PALSAR data.

***Index Terms*—** SMAP, Radar, RFI

1. INTRODUCTION

The planned Soil Moisture Active Passive (SMAP) mission has the scientific objective of measuring and monitoring both soil moisture and freeze/thaw state globally from space with unprecedented resolution and accuracy. In order to accomplish this objective, the planned mission will make both active radar and passive radiometer measurements at L-Band. The higher resolution radar measurements are obtained by utilizing synthetic aperture radar (SAR) processing, and these data will be combined with the established accuracy of coarse-scale radiometer soil moisture retrievals to produce soil moisture estimates at 9 km. The relative error of estimates of soil moisture based on combined active-passive measurements is required to be less than 0.04 [cm^3/cm^3] volumetric soil moisture. The levied accuracy requirements for the radar co-pol and cross-pol measurements are 1.0 dB and 1.5 dB respectively. The SMAP radar is operating at L-band due to the demonstrated sensitivity of this band to the soil moisture. SMAP transmits a 1 MHz linear chirp signal within the allocated frequency band from 1217.5 to 1297.5 MHz. This band is also shared by Global Navigation Satellite Systems (GNSS), like GPS, and radiolocation services, which are mainly long range air route surveillance radars and military air defense radars. The signals from these sources will interfere with the ground return echo of the SMAP radar, and they are regarded as radio frequency interference (RFI). Studies had been conducted [1], [2], and they suggest that RFI could contaminate or corrupt the SMAP radar measurements. To satisfy the high accuracy requirements of the SMAP measurements, the errors allocated to RFI for the co-pol and cross-pol radar data are 0.4 dB and 0.8 dB respectively. Some features of the SMAP radar electronics are specifically designed to mitigate RFI contamination, and the SMAP data processing team has investigated and evaluated several algorithms to detect and correct RFI contaminated signals. These two aspects of the SMAP radar will be presented in the following sections.

2. SMAP RADAR ELECTRONICS – SYSTEM DESIGN FOR RFI MITIGATION

Some terrestrial radars have high transmit power (e.g., Cobra Dane of the US Air Force generates approximately 15.4 MW of peak RF power). The maximum receive power in the front end of the SMAP radar receiver will be 2.4 W in the worst scenario. The radar is protected from damage with a limiter in the cal-loop assembly. Beyond ensuring that the radar will survive the most severe RFI, it will further be designed with RFI mitigation capabilities that include: 1) A tunable operating frequency to allow the instrument to avoid the particularly noisy regions of the spectrum over specific regions of the Earth; 2) Sharp RF/digital receiver filtering and a high degree of out-of-band interference rejection (80+ dB); and 3) Supplemental radar telemetry for flagging any range lines contaminated by RFI, so that these bad data can be removed in ground data processing. A key related requirement for the radar receiver is that out-of-band interference contributes less than 0.4 dB (10%) power detection error in the echo measurement. Radar requirements for frequency agility and selectivity are driven by this accuracy requirement.

[1] The SMAP mission has not been formally approved by NASA. The decision to proceed with the mission will not occur until the completion of the National Environmental Policy Act (NEPA) process. Material in this document related to SMAP is for information purposes only.

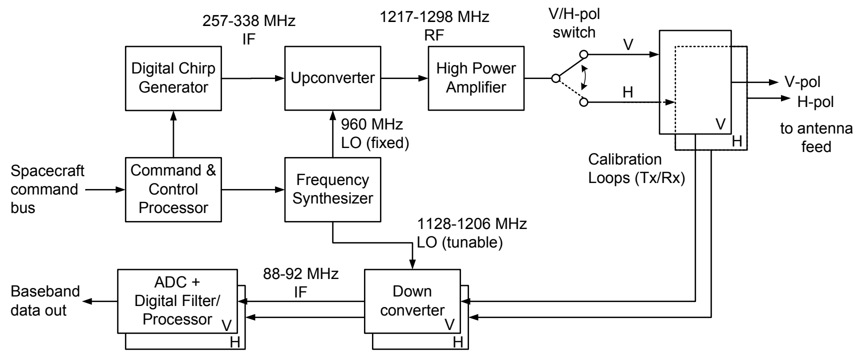


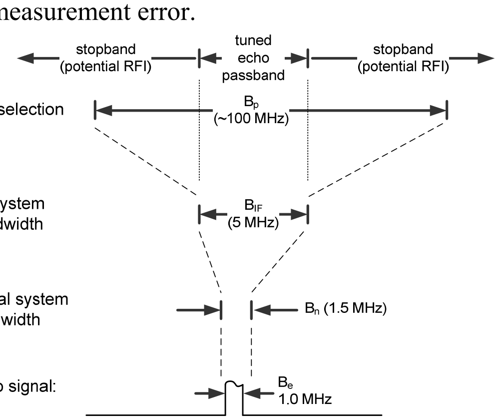
Figure 1 - SMAP tunable radar architecture for avoiding RFI.

2.1. Control of Radar System Parameters

The radar hardware is designed with a simple, state-machine based command-and-control processor (CCP), which accepts new radar parameters once per antenna rotation (~4.6 s) via command from the spacecraft. As RFI frequency bands may vary within a scan of the SMAP antenna, up to 16 separate radar operating frequencies (one for each 22.5° scan segment) are updated every rotation from a spacecraft lookup table. RF operating frequencies for the 1-MHz chirp channels are adjustable over ~1217-1298 MHz, in 1.25 MHz steps. The radar also has a receive-only ("RFI survey") mode for monitoring the terrestrial RFI environment. This mode is used during mission operations to build a database of interference spectra, as seen from the orbiting instrument's perspective.

The radar design uses a hybrid digital-analog approach to update the radar operating frequencies dynamically in orbit as shown in Fig. 1. The transmit chain uses direct-digital synthesis technology inherited from the Aquarius instrument [3] to generate the pair of tunable frequencies for V- and H-pol, 1-MHz chirp pulses, but modified to accept frequency updates digitally from CCP. The receiver chain uses a single-stage heterodyne downconverter with tunable LO and FPGA-based back-end digital processor. After A/D conversion, the custom FPGA digital data processor performs further demodulation and filtering at fixed channel frequencies. Both the chirp generator frequencies and synthesized down-converter LO frequency are commanded in real time via a spacecraft lookup table, based on the observatory's present latitude and longitude. With the heterodyne approach, the analog IF filter (preceding A/D conversion) provides excellent out-of-band rejection, which in turn significantly boosts the dynamic range of the digital portion of the receiver in noisy RFI environments.

To get a high level of RFI suppression, the receiver filter stages are configured as a series of "funnels" for blocking the interference. This scheme is shown in Fig. 2. Filter bandwidth becomes progressively narrower down the chain, to help maintain receiver dynamic range in the presence of out-of-band interference. Filtering includes: gradual RF pre-select filtering with ~1210-1310 MHz passband; a higher-order IF bandpass filter (90 MHz center, 5 MHz half-power bandwidth) with sharper rolloff and rejection (80 dB down, ±7 MHz from center-of-band); and very sharp digital filtering of individual 1-MHz echo channels (72 dB down, ±1 MHz from center). The receiver's dynamic range in the absence of RFI is 25 dB (min/max echo levels from -106 dBm to -81 dBm, referenced to the RF input). When out-of-band RFI is present, the receiver can tolerate interference up to -37 dBm (69 dB above the minimum echo level) before exceeding 0.4 dB measurement error.



Parameter	RF input-referred power level
Maximum allowed out-of-band RFI (in stopband)	-37 dBm
RF gain compression limit (e.g., due to RFI in passband)	-60 dBm
Max echo level	-81 dBm
Min echo level	-106 dBm
RF/digital system noise floor	-106 dBm

Figure 2 - RFI filtering "funnel" in the radar RF/digital receiver.

Several telemetry functions are designed into the receiver electronics to flag data blocks corrupted by RFI. A "receive power monitor" flag is set whenever strong out-of-band interference causes a gain compression error in the RF front-end, upstream of the IF filter. An A/D converter "saturation flag" detects range lines where strong in-band RFI causes one or more voltage samples to be clipped in the receive-window period. “Noise-only” power measurements in the digital processor are accumulated on short time scales (every PRI, or ~350 μs) to facilitate detection of pulsed RFI. These telemetry fields serve as an important tool in ground data processing to identify and throw away contaminated echoes and noise only measurements, before blocks of raw SAR data are processed further.

3. SMAP GROUND RADAR PROCESSING – ALGORITHM FOR RFI DETECTION

With a tunable radar architecture, the operating frequency can be moved away from frequency bands where strong RFI is identified at certain geographical locations. In addition, the flags from the radar telemetry data provide very useful information to the ground data processing because range lines that are corrupted by high RFI signals can be identified. With these mitigation and detection mechanisms, however, there are strong evidence to show that some RFI, with power lower than the levels necessary to trigger the telemetry flags but still high enough to cause a degradation of the measurement accuracy of 0.4 dB, can regularly appear in the radar data. Effective detection and correction algorithms are necessary to meet the science measurement requirement during ground data processing. In order to develop these algorithms, the nature of the observed RFI over the whole globe is characterized with existing ALOS PALSAR data. Several approaches for detecting RFI have been considered. One algorithm, the Slow-Time Thresholding (STT) algorithm, has been studied in detail. This algorithm has been tested with PALSAR data sub-banded to resemble the 1 MHz SMAP data, and it has been demonstrated to be effective in detecting RFI.

3.1. RFI Characterization with PALSAR Data

ALOS PALSAR is a polarimetric L-band SAR system developed by JAXA. PALSAR is in a circular sun-synchronous orbit with an altitude of 692 km, which is close to the SMAP altitude of 685 km. The center frequency of PALSAR is 1270 MHz, and the transmit and receive bandwidths are 28 MHz and 32 MHz, respectively. The received bandwidth covers 40% of SMAP’s allocated bandwidth. In addition, this frequency band overlaps the operating frequencies of many terrestrial radars, which will present RFI to both PALSAR and SMAP. PALSAR data provide a source to evaluate possible interference signals and their associated temporal variations. More than 300 data items were used in this analysis. This data set is comprised of PALSAR collections mostly taken over the U.S., but also including some sites over Europe and Asia. The data suggest that most observed RFI is from pulsed radars. An examination intended to characterize the nature of RFI yielded 87% of RFI observed from pulsed sources and 13% from “other” sources including CW. For the most part, sources seem to be relatively narrow band (2-4 MHz). Some evidence suggest that there are some frequency bands that are globally more “clear” than others, but no band is completely clear. Europe seems to be worse than CONUS, and there are some other unidentified sources in urban regions (e.g., Hong Kong), that are very complex. Characterization studies using PALSAR are by no means comprehensive, and further study is required. The Aquarius radar will launch in June of 2011, with data expected to be returned in early July of 2011. Aquarius will give global insight into RFI within the frequency band of 5 MHz centered on 1260 MHz. The Aquarius data will provide another source to examine and verify RFI environment.

3.2. Slow-Time Thresholding Algorithm

According to the analysis of the PALSAR data, most of the RFI is from pulsed sources. Furthermore, it is observed that RFI occurs at a rate much less than the SMAP nominal PRF which is 2.9 kHz. The Slow-Time Thresholding (STT) algorithm looks at the slow-time series associated with a given range sample, sets an appropriate threshold, and identifies any samples that exceeds this threshold as RFI events. For each (I, Q) sample collected within the receive window of the radar echo, its power is compared to the median of neighboring range lines using a moving median filter with 101 elements in the current design. RFI is flagged if the ratio of the measured power to the moving median power is greater than 4 standard deviations above the median.

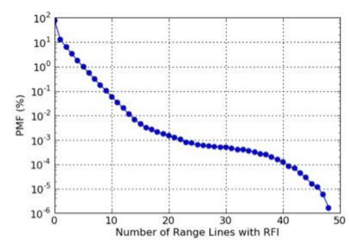


Figure 3 - Estimated probability distribution of RFI contamination in a SMAP synthetic aperture.

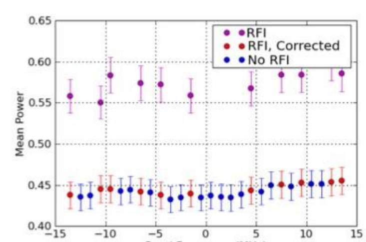


Figure 4 – Evaluation of the modified correction algorithm.

This algorithm is applied to the simulated SMAP data created by bandpass-filtering PALSAR data with a 1 MHz bandwidth centered at 32 frequencies ranging from 1254.5 MHz to 1285.5 MHz, in 1 MHz intervals. As the nominal

PRF and receive window duration of SMAP are different from PALSAR, the subband data are rearranged in the time domain to reflect the SMAP timing. The simulated data can then be viewed as a two-dimensional array: the range samples in "fast time" for each pulse in one dimension, by the pulse number associated with each range line in "slow time." The Slow-Time Thresholding technique is can then be applied to these data, and the number of range lines with RFI detected in the pixel counted at each frequency. The high resolution radar measurements are obtained by applying SAR processing to the SMAP data for an integration time of 42 ms, or 112 range lines. From the analysis of the simulated SMAP data, it is concluded that the probability of having more than 5 SMAP range lines within a synthetic aperture contaminated by RFI is less than 1% for any randomly chosen 1 MHz over North America as shown in Fig. 3. Removing range lines will distort the impulse response function of the azimuth compression, but the measurement accuracy will degrade more than 0.4 dB only if 15 or more range lines (out of 112) are excised, which has appears to be very low likelihood.

In addition to detecting RFI, RFI correction algorithms are evaluated in order to improve data accuracy. One possible algorithm is simply to replace a RFI contaminated azimuth sample by its previous neighbor. However, this technique will introduce a positive radiometric bias in the backscatter cross-section estimate after SAR processing, because replacing sample is coherent with its previous datum. To remove this bias, the correction algorithm is modified to add a random phase to the duplicated range sample, with a random distribution determined by the statistics of the data. Two PALSAR data sets are utilized to verify this modified algorithm: one with significant RFI (Alaska) and one with very little RFI (New Zealand). Each data set is sub-banded into 28 synthetic SMAP data streams with 1 MHz bandwidth. Each data set from Alaska is run through the STT algorithm. The images are formed with and without applying the correction algorithm, and the differences are shown in Fig. 4. The "RFI-free" data from New Zealand are used to calibrate the frequency response in each of the 28 sub-bands.

The analyses with the PALSAR data show that both the STT detection algorithm and modified correction algorithm are effective tools to improve RFI contaminated data. With these techniques, the allocation in the SMAP error budget of 0.4 dB for RFI contamination seems reasonable. However, the difference in the antenna pattern between PALSAR and SMAP may impact this initial conclusion. The planar array PALSAR antenna has different sidelobe structure than the SMAP circular reflector, and it might be more favorable to the use of STT. These algorithms will be further tested with Aquarius data in the near future, and modifications to these algorithms might be required.

4. CURRENT STATUS OF SMAP RADAR

Fabrication, assembly and test of the SMAP radar RF and digital brassboards are currently underway at JPL at the unit and assembly levels. Results show that the radar receiver meets or exceeds requirements on tuning lock time, RF/analog filtering and digital filtering. The measured analog IF filter rolloff response was -60 dB at 6.3 MHz from center of band, and -80 dB at 7.0 MHz from center. Digital filter response rolls off to -72 dB at 1 MHz offset from the center of each echo measurement channel. Two-tone frequency tests (injecting a weak signal plus strong CW interferer) demonstrate less than 0.3 dB signal compression for out-of-band interference levels up to –37 dBm at the RF input of the receiver. Initial tests of the receive power monitor circuit show detection sensitivity for pulsed RFI greater than or equal to 5 μs pulse width; detection response time and sensitivity improve to 2 μs for very strong RFI (> -27 dBm at the RF input). Integrated RF/digital brassboard testing is planned for Summer-Fall 2011 to verify the RFI mitigation architecture at the radar subsystem level.

Different methodologies for detecting RFI have been studied and one algorithm -- threshold detection in time domain -- has shown good promise. When this technique is applied to simulated SMAP data created from PALSAR data, the probability of more than 5 range lines being contaminated by RFI is less than 1%. The percentage of data having an error larger than 0.4 dB is well below 2%, which is the current allocation of data loss to RFI. As time evolves, the RFI environment will change as more terrestrial radars are built or upgraded. These trends will be tracked, and the optimal detection and correction algorithms will be correspondingly updated.

5. ACKNOWLEDGMENT

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6. REFERENCES

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